AHV-IV 364 VIBRATOR THEORY OF OPERATION

INOVA GEOPHYSICAL

Table of Contents

INTRODUCTION

The AHV-IV 364 vibrator (Commander), a 60,000-lbs modern seismic vibrator, is a hydro-mechanical system driven by a servo-valve assembly that is controlled electronically. To show some basics of the AHV-IV 364 vibrator, a schematic model is illustrated in Figure 1.

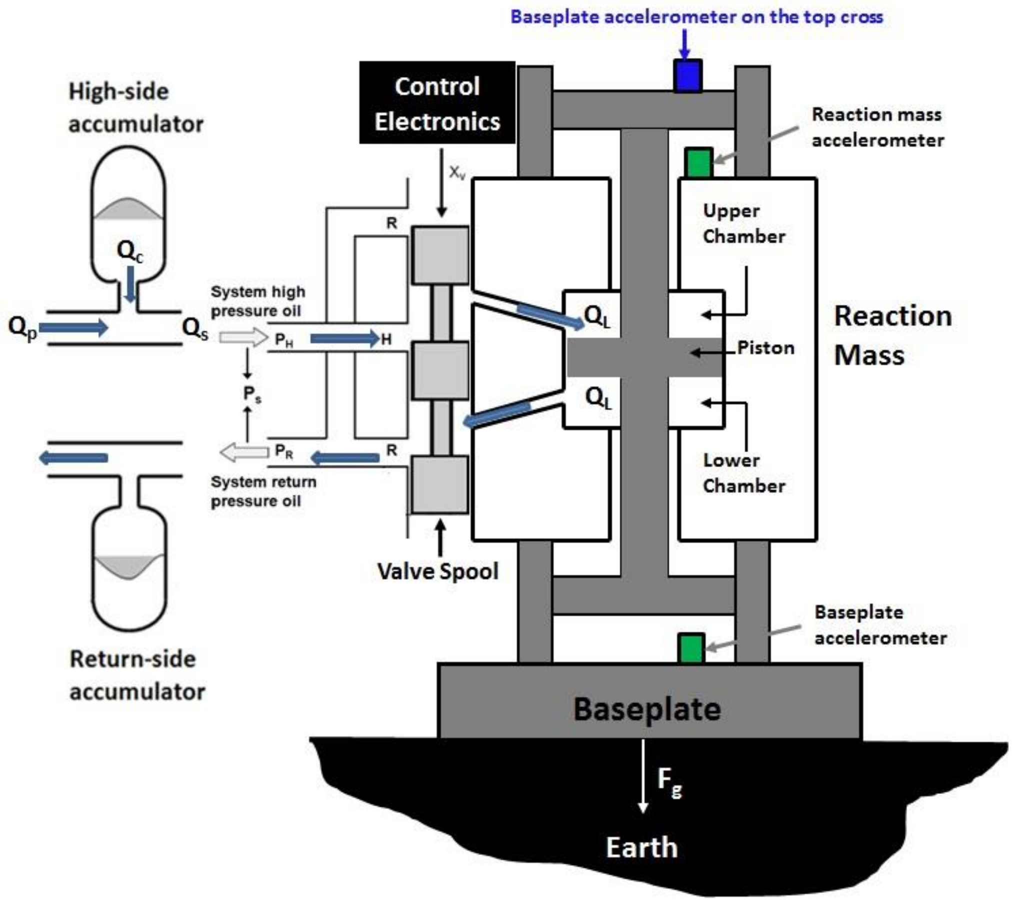

Figure 1 – A schematic model of the AHV-IV 364 vibrator.

From left to right, hydraulic oil is pumped into supply pressure hoses, which consist of a system high pressure hose and a system return-pressure hose. These hoses connect to the high pressure and return pressure ports on the main-stage servo-valve. In the figure, high and return pressure ports are marked with “H” and “R”, respectively. Two accumulators are placed on the high-pressure and return-pressure sides to damp ripples and fluctuation of the supply pressure. The high-pressure hydraulic oil flows out of the main-stage servo-valve and is fed alternately into the upper and lower chambers to drive the reaction mass to move up and down. For example, the arrows in Figure 1 show that a high-pressure hydraulic oil flows in the main-stage servo-valve through the high-pressure port and flows out of the main-stage servo- valve through one control port. Then, it is fed into the upper chamber to drive the reaction mass to move up. Meanwhile, the same amount hydraulic oil in the lower chamber flows out and moves into the main-stage servo-valve through the other control port. Through the return pressure port on the main-stage servo-valve and system return pressure hoses this hydraulic oil returns back to the reservoir tank. The force generated by the motion of the reaction mass is equally and oppositely applied to the piston. Then, through the vibrator baseplate, this force is radiated into the ground. This force is the vibrator ground force and can be estimated by using a “weighted-sum” of accelerations of the reaction mass and the baseplate.

GROUND RESONANCE

Ground resonance is the property of an elastic ground. The resonant frequency is determined by its mass and stiffness. When the vibrator baseplate is coupled or loaded to the ground, the baseplate can feel the hardness and softness of the ground. Meantime, it can also feel the size of the ground that is pushed down or pulled up. This size of the ground can be computed as the mass of the ground. Ground resonance can cause an imbalance in the vertical motion of a vibrator baseplate. Often, it can be reorganized using the phase shift between the reaction mass acceleration and the baseplate acceleration.

- When the phase discrepancy is greater than -90 degrees, the corresponding frequency is the resonant frequency.

- **When the phase discrepancy approaches to -135 degrees, the fundamental force and the amplitude spectrum of the vibrator ground force starts to decline.**

EFFECTIVENESS OF GROUND RESONANCE ON THE WEIGHTED-SUM GROUND FORCE

The vibrator ground force can be estimated by using a “weighted-sum” of accelerations of the reaction mass and the baseplate. Accelerometers are strategically mounted on the vibrator structure to record accelerations of the baseplate and the reaction mass. The weighted-sum ground force is an estimate of the true vibrator ground force (F_g). This method assumes that the baseplate acts as a rigid body, and a full coupling of the baseplate and the ground is achieved. Under these assumptions, the weighted-sum ground force is obtained by summing weighted baseplate and reaction mass accelerations. In this case,

$$F_g \approx F_{ws} = M_{rm}A_{rm} + M_{bp}A_{bp} \qquad (1)$$

where F_g is the true vibrator ground force; F_{ws} is the weighted-sum ground force; M_{rm} and M_{bp} are the masses of the reaction mass and the baseplate, respectively; A_{rm} and A_{bp} are the accelerations of the reaction mass and the baseplate, respectively.

In order to explain the relationship of contribution to the weighted-sum ground force from the reaction mass and the baseplate, the frequency response is necessary. Figure 2 shows a theoretical frequency response between the reaction mass acceleration and the baseplate acceleration where the reaction mass acceleration is the input signal while the baseplate acceleration is the output signal responding to the input. The amplitude frequency response (top graph) and a phase frequency response (bottom graph) are illustrated. Below the resonant frequency, the reaction mass force is dominated in the weighted-sum ground force and the reaction mass acceleration and the baseplate acceleration are in-phase. After the resonant frequency, the weighted-sum ground force is dominated by both reaction mass force and baseplate force. Meantime, the phase of the baseplate acceleration starts to depart from the phase of the reaction mass acceleration. In actuality, the baseplate force attempts to cancel the reaction mass force because of the out-of-phase relationship. This leads to the fact that the vibrator hydraulic system needs to produce more force to compensate for the force cancelled by the baseplate. Eventually, the hydraulic system limitations will be reached and the vibrator output force will decline often resulting in an unstable servo-valve system.

In summary, the ground resonant frequency defines the frequency range the baseplate force makes a positive contribution to the vibrator ground force if its acceleration is in-phase with the reaction mass acceleration. Otherwise, it will cancel the force generated by the reaction mass and reduce the vibrator ground force.

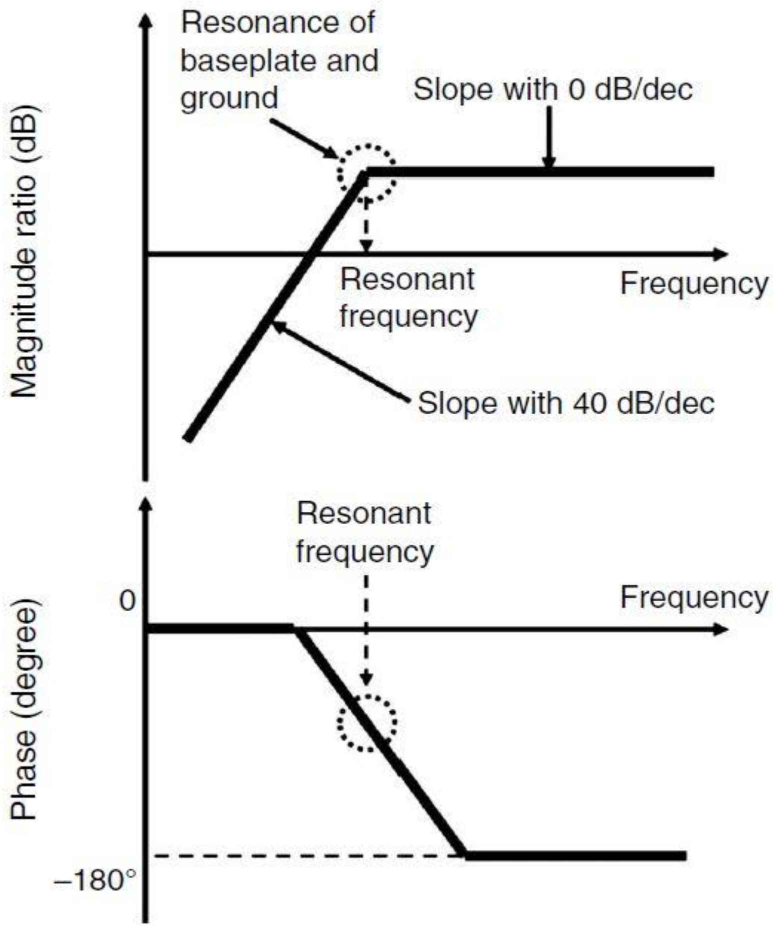

Figure 2 – Frequency response of the reaction mass acceleration and baseplate acceleration.

VIBRATOR QUALITY CONTROL METHODS

In field, peak and fundamental force can be measured in a variety of ways. These methods include radio similarities, wireline similarities, post sweep QC data, independent accelerometer analysis. Radio similarities transmit a selected signal, usually a ground force estimate, from the vibrator controller to be compared to the pilot signal using software to analyze force, phase, and distortion. This ground force signal is a calculated weighted-sum estimate based on the accelerometer signals mounted on the vibrator actuator. The radio similarity method is a useful tool with reasonable resolution but due to radio communication limitations, only one vibrator can be analyzed at a time using an available software package.

Wireline similarities offer good resolution and the ability to compare all vibrators at the same time for the same sweep. Generally, a ground force estimate and pilot signal is directly connected to a seismic channel. The ground force estimate is calculated using the loop or similarity accelerometer signals and attenuated to a low-level voltage suitable for seismic channel A/D converters. After all vibrator signals are collected, a comparison of force and phase can be evaluated. While this method offers the best resolution, it is usually only performed occasionally due to the set up time required for this test.

Post sweep QC data for each vibrator is usually transmitted back to the recording truck after each sweep. The post sweep QC data generally includes peak and average force, phase, and distortion values as calculated by the vibrator source controller. Some source controllers also transmit a cross-correlation wavelet of the vibrator’s pilot signal and ground force estimate. Radio communications and time constraints cause a limitation on the resolution of the correlation wavelet, but there is sufficient resolution to plot an estimate of the force and phase of the vibrator output. The post sweep QC data is the most used quality control tool and it allows an observer to compare a fleet of vibrators after each sweep to ensure all vibrators are performing similarly. Another quality control method used to evaluate vibrator performance uses magnetic-mounted, independent accelerometers with an acquisition system to calculate force, phase, and distortion for a vibrator. This method can offer very good resolution, but is usually only performed on one vibrator at a time. This method can sometimes give different results, as seen in the previous methods above due to the accelerometer location and strength of the magnet used to couple the accelerometer to the reaction mass and baseplate.

In summary, all these methods provide an evaluation on the vibrator performance based on the acceleration signals of both reaction mass and baseplate. Therefore, the accelerometer locations, especially the baseplate accelerometer location, will significantly impact the accuracy of the weighted-sum ground force. What is the best location within the baseplate to position the baseplate accelerometer?

BASEPLATE ACCELEROMETER POSITION ON THE AHV-IV 364 VIBRATOR

Usually, the baseplate accelerometer is mounted on the top cross of the stilt-structure, for example the AHV-IV 362 vibrator. The stilt-structure consists of the top cross, the tie rods, the piston and the bottom cross. Then, it is integrated with the baseplate firmly. Totally, it is called the baseplate driven structure. Figure 1 illustrates the cross-section of this structure. **The blue square marked as baseplate accelerometer on the top cross in Figure 1 indicates the placement of the baseplate accelerometer in conventional fashion.**

The reason why the baseplate accelerometer is placed on the top cross is because the baseplate is not a rigid body. It flexes as the vibrator shakes. The flexure becomes severe at high frequencies. Placing the baseplate accelerometer at different locations within the baseplate will result in different weighted-sum ground forces. The stilt-structure acts as a damper that attenuates the flexures of the baseplate. When the baseplate accelerometer is placed on the top cross, it results in a stable weighted-sum ground force. This baseplate accelerometer configuration has been applied on the vibrator for over 40 years. In QC plots, the fundamental force and its amplitude spectrum is flat. Observers have been used to seeing flat fundamental force and amplitude spectrum. However, as the stilt-structure attenuates the flexural motions of the baseplate, it also attenuates the ground motion. More precisely speaking, at high frequencies the stilt-structure isolates the baseplate accelerometer from the ground motion. The baseplate accelerometer detects more motion of the stilt-structure than the motion of the ground. Therefore, the weighted-sum ground force is not consistent with the vibrator down-going force energy even though its amplitude spectrum is flat.

The AHV-IV 364 vibrator carries a stiffer baseplate that is 2.5 times stiffer than the standard baseplate but has only an 8% increase in weight. With the stiffer baseplate, the coupling of the baseplate and the ground is improved under various loading conditions, and the vibrator performs robustly. Because the baseplate is stiffened significantly, the motion of the baseplate during sweeping can be repeatable. Precisely speaking, the vertical motion of the baseplate during sweeping can be described as a bird flapping its wings. In the baseplate motion of the bird flapping its wings, there is one spot within the baseplate that its motion is always in vertical direction. This place is chosen as the baseplate accelerometer location instead of the normal position which is on the top cross.

ADVANTAGES FROM THE AHV-IV 364 VIBRATOR

For an AHV-IV 364 vibrator from, the baseplate accelerometer is mounted on the top surface of the baseplate and the reaction mass accelerometer is installed on the top of the reaction mass as depicted in Figure 1. **The positions of accelerometers are shown in green squares.** There are two advantages with this baseplate accelerometer location. The first advantage is that it can offer a very good agreement between the weighted-sum ground force estimate and the vibrator down-going energy. The second advantage is that it provides a stronger force-energy than the baseplate accelerometer on the top cross.

Data Example 1

A test was performed in 2009 in West Texas where two different vibrators (an AHV-IV 362 vibrator and an AHV-IV 364 vibrator) were used to shake a 2D line separately. Vibrator signatures were recorded for each sweep for both vibrators. The baseplate from each vibrator was placed approximately 1 meter from a 3-component geophone. A 1-160 Hz sweep was designed with a -2 dB/octave dwell from 1 to 8 Hz for 3 seconds. An appropriate taper was selected for maximum vibrator performance without exceeding reaction mass stroke limits. Figures 3 and 4 show amplitude spectrum results from the vertical component of the geophone, the post sweep QC, and from recorded vibrator signatures.

In Figures 3(a) and 4(a), it can be seen that above approximately 110 Hz, the amplitude spectrum of the surface geophone at 1 meter apart from the baseplate shows a decline in power. In the case of the AHV-IV 362 vibrator, Figures 3(b) and 3(c) do not reflect the decline in output power. The amplitude spectrum in Figures 3(b) and 3(c) are composed of accelerometer signals that are located on the reaction mass and the top cross of the baseplate driven structure.

In Figures 4(b) and 4(c), the case of the AHV-IV 364 vibrator, the decline in output power can be seen using quality control tools. While these plots may not look like what an observer is accustomed to seeing, it is a better representation of the true power spectrum as seen in Figure 3(a). When comparing Figures 3(a) and 4(a), it can be seen that AHV-IV 364 vibrator generates more force than the AHV-IV 362 vibrator, but falls short of producing a flat amplitude spectrum in frequencies above approximately 120 Hz. The weighted sum estimate calculated by the vibrator source controller is a more accurate representation of the true output force. At approximately 120 Hz, the vibrator exceeds the limits of the servo-valve and hydraulic system and the output force declines at a slower rate than the AHV-IV 362 vibrator.

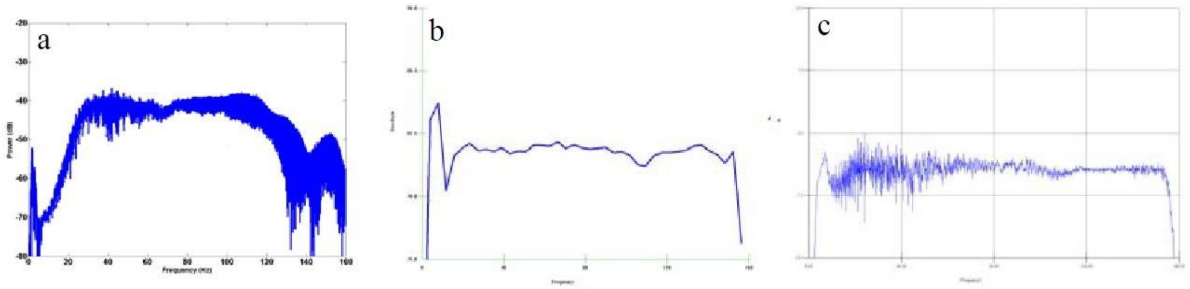

Figure 3 – The AHV-IV 362 vibrator. (a) Amplitude spectrum from surface geophone at 1 meter distance from baseplate. (b) Amplitude spectrum as seen in QC sent post sweep. (c) Amplitude spectrum using vibrator signature files as local force meter.

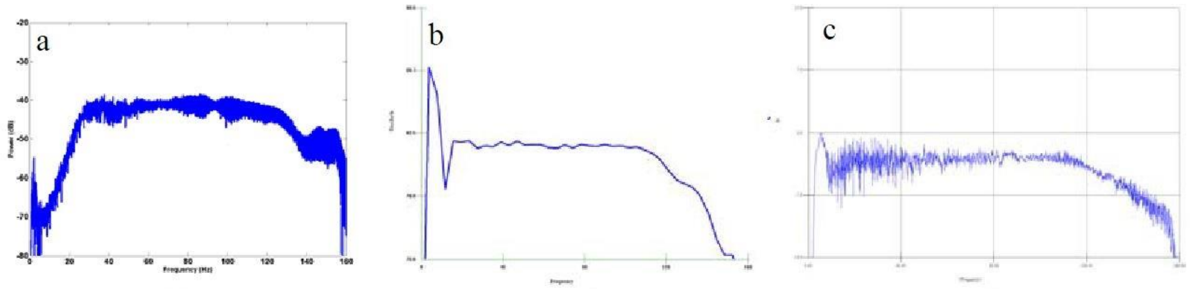

Figure 4 – The AHV-IV 364 vibrator. (a) Amplitude spectrum from surface geophone at 1 meter distance from baseplate. (b) Amplitude spectrum as seen in QC sent post sweep. (c) Amplitude spectrum using vibrator signature files as local force meter.

Data Example 2

In 2008, a test was performed in Southeast Texas with two vibrators; one is the AHV-IV 362 vibrator and the other is the AHV-IV 364 vibrator. The vibrators were placed at the top of a downhole well with 20 levels of 3C geophones at 50 ft intervals beginning at 50 ft. Below are two amplitude spectrums for each vibrator performing a linear sweep from 2 to 160 Hz over 20s at a target force of 42,000 lbs. The first plot is from the post sweep QC, and the second plot from the Z-axis of the 1000-ft downhole geophone.

In plots 5 and 6, it can be seen that the 1000-ft downhole amplitude spectrum begins to decline at approximately 120 Hz. For the AHV-IV 362 vibrator, the post sweep QC amplitude spectrum does not indicate a decline in output power. For The AHV-IV 364 vibrator, the post sweep QC amplitude spectrum does show a decline in output force at approximately 130 Hz. As demonstrated in the plots, the weighted-sum ground force estimate more closely reflects the amplitude spectrum from the measured downhole signal using the AHV-IV 364 vibrator. When comparing Figures 5(a) and 6(a), it can be seen that in the frequency range from 80 Hz to 160 Hz the AHV-IV 364 vibrator generates approximately 5 dB more force than the AHV-IV 362 vibrator generates.

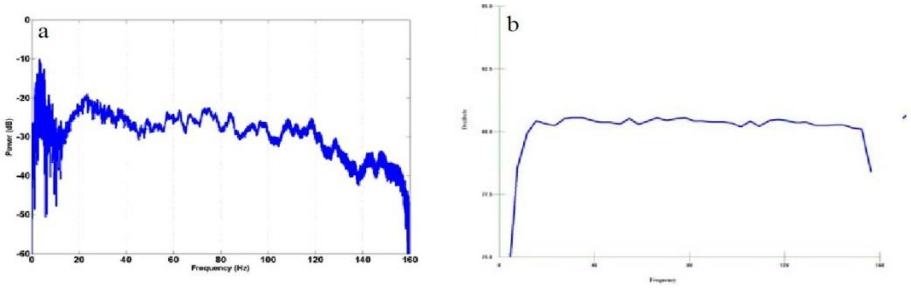

Figure 5 – The AHV-IV 362 vibrator. (a) Amplitude spectrum from 1000 ft downhole geophone (b) Amplitude spectrum as seen in QC sent post sweep.

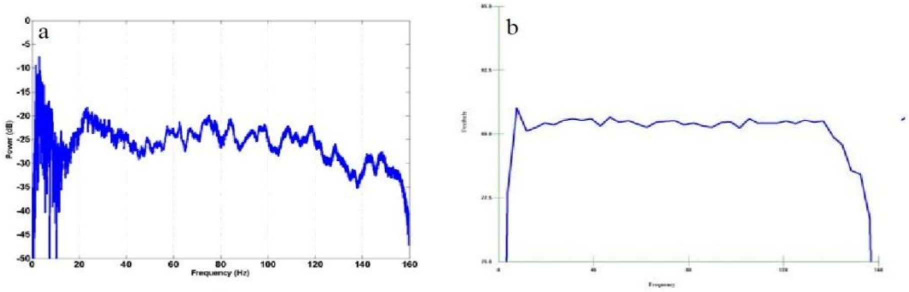

Figure 6 – The AHV-IV 364 vibrator. (a) Amplitude spectrum from 1000 ft downhole geophone (b) Amplitude spectrum as seen in QC sent post sweep.

CONCLUSIONS ON THE AHV-IV 364 VIBRATOR

Increased rigidity of the AHV-IV 364 vibrator baseplate improves the accuracy of the weighted-sum ground force estimate, and more closely reflects the true signature as is detected by surface seismic and downhole measurements. The AHV-IV 364 vibrator with the baseplate accelerometer located on the bottom (the green square in Figure 1) can offer a good estimate of the ground force representing the true vibrator down-going force energy. However, sometimes the amplitude spectrum of the weighted-sum ground in QC plots is not a constant curve, especially at high frequencies. These QC plots often make observers upset because of an expectation of the flat curve.

Figure 7 shows an example of the AHV-IV 364 vibrator performing a linear sweep from 6 Hz to 200 Hz in 20s at 80% force. Figures 7b and 7d show the fundamental force and amplitude spectrum of the weighted-sum ground force, respectively. Two plots demonstrate that the ground force declines starting at 6 seconds corresponding to approximately at 65 Hz.

Figures 7a and 7c explain why the force starts to decline at 65 Hz. Figure 7a displays the phase of the baseplate force in voltage (red) and the reaction mass force in voltage (green) in wiggle traces zoomed in the time window from 6 to 6.1 seconds. It clearly shows that the phases of the baseplate and the reaction mass are opposite (out of phase). Figure 7c shows the phase difference between the baseplate acceleration and the reaction mass acceleration. It is seen that at 6 seconds the phase difference is -135 degrees. The problem is caused by the ground surface. Possibly, the surface of the ground is loosened. There are some ground resonances in the frequency range from 30 to 60 Hz. These ground resonances cause the phase of the baseplate to shift 135 degrees from the phase of the reaction mass. From equation 1, we know that the force generated by the baseplate cancels the force generated by the reaction mass leading to the ground force reduction.

This example shows that the baseplate accelerometer detects the ground motion and its impact on the vibrator performance. The weighted-sum ground force reflects the true response of the ground. This weighted-sum ground force is the true representation of the vibrator down-going force energy.

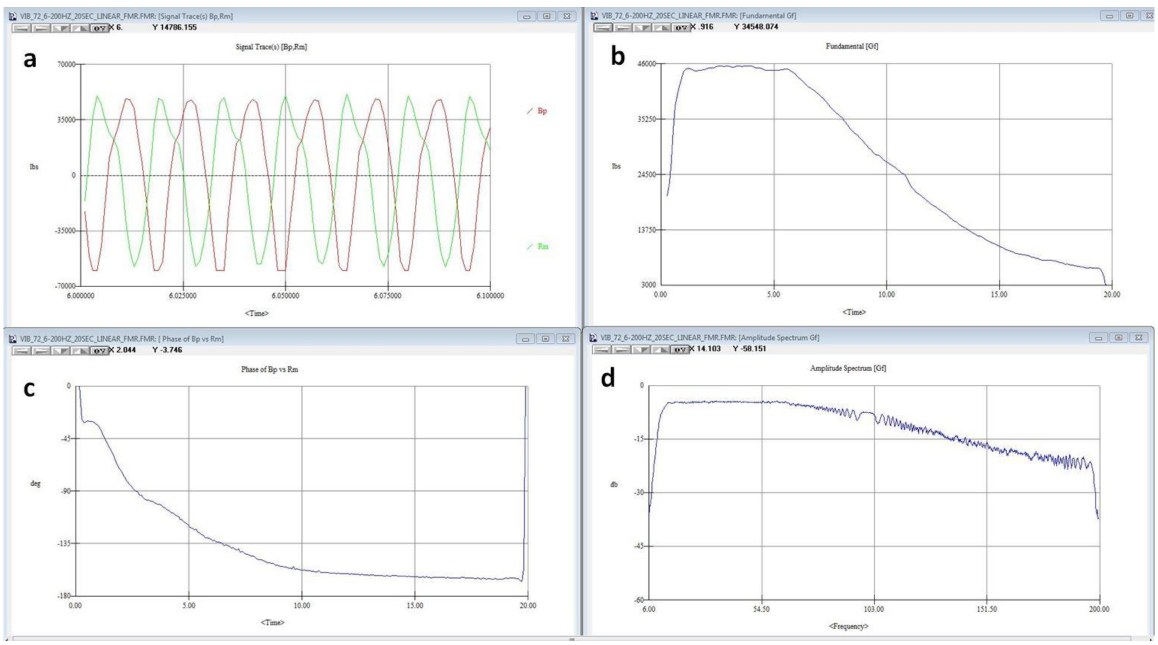

Figure 7 – The AHV-IV 364 vibrator. (a) The wiggle traces of the reaction mass and baseplate accelerations. (b) The fundamental force. (c) The phase difference between the reaction mass acceleration and the baseplate acceleration. (d) The amplitude of the weighted-sum ground force.

HOW TO PROVE THAT VIBRATOR PERFORMANCE DECLINE DUE TO GROUND RATHER THAN MECHANICAL OR ELECTRICAL PROBLEMS?

Here are some guidelines to check.

I. Vib Pro settings

If Vib Pro control electronics is used for vibrator control, check the limit control settings. The 80 mA is required by operating Moog pilot valve. The following figures (Figures 8, 9 and 10) show correcting settings. These settings assure there are no wrong control settings that limit the vibrator.

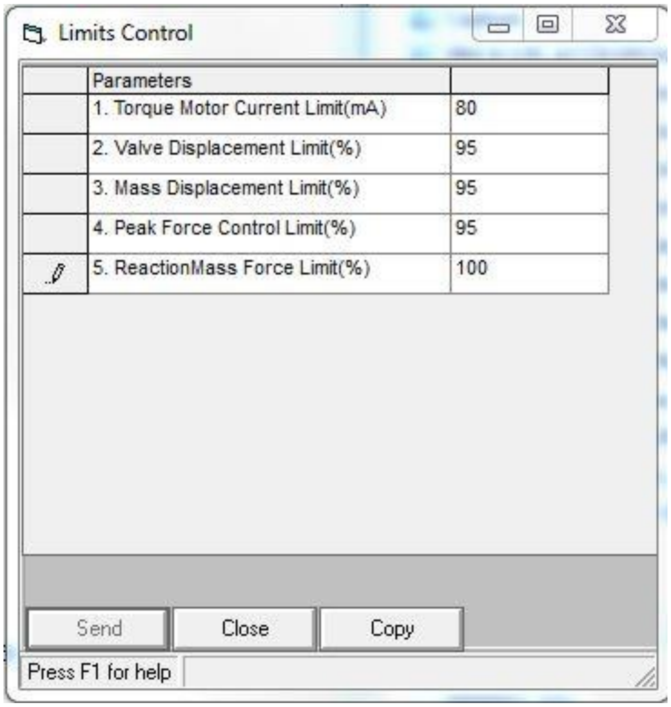

Figure 8 – Vib Pro Limits Control settings.

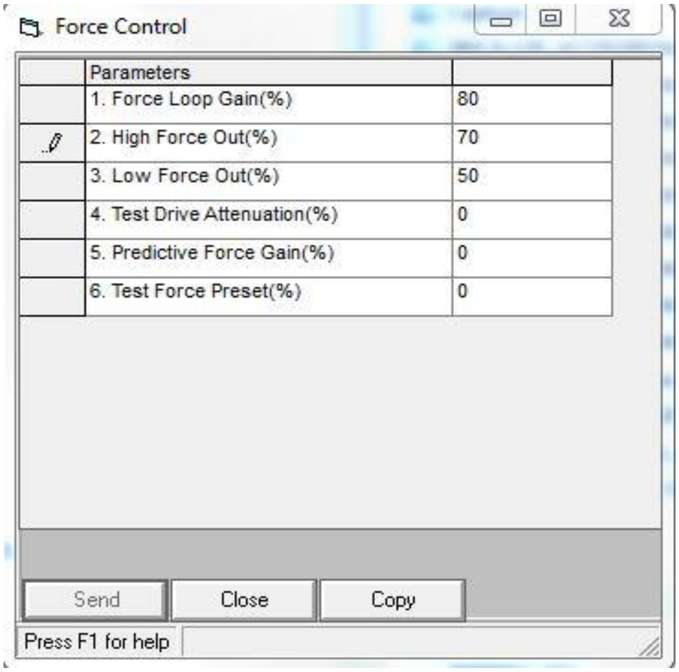

Figure 9 – Vib Pro Force Control settings.

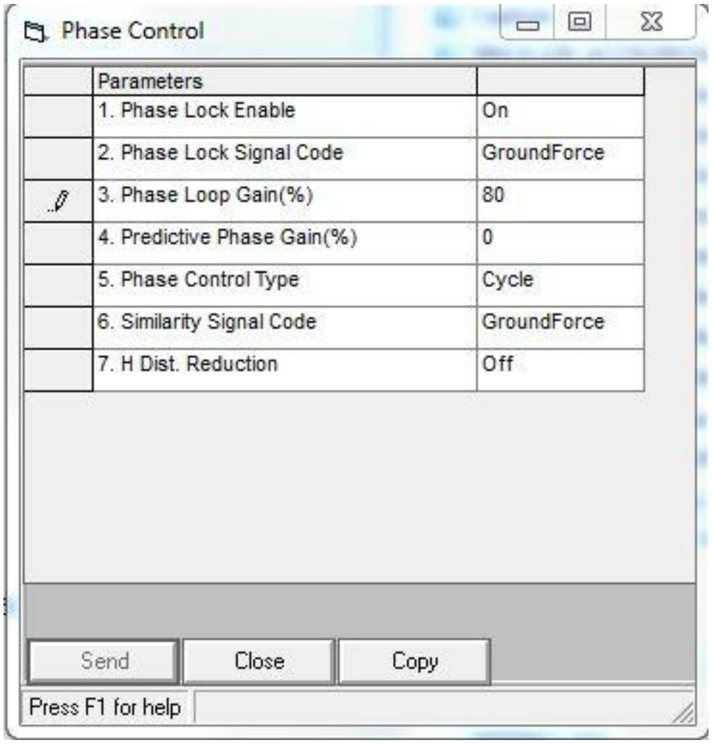

Figure 10 – Vib Pro Phase Control settings.

II. Vibrator Settings

Settings	AHV-IV 364	AHV-IV 380	UniVib
Pelton DR Valve	Must be installed and enabled	Must be installed and enabled	Must be installed and enabled
Centering airbag pressure	80 psi	85 psi	60 psi
Hold-down airbag pressure	80 psi	80 psi	70 psi
Hold-down pressure	2100 psi	2100 psi	2200 psi

III. Plotting the phase relationship between the reaction mass acceleration and the baseplate acceleration (the bottom-left graph)

The AHV-IV 364 vibrator performs a linear sweep from 5 Hz to 150 Hz in 10s at 70% of force on hard gravel track. The phase (the bottom-left graph) approaches the -135 degrees at the end of the sweep. The force drops slightly at the end of the sweep.

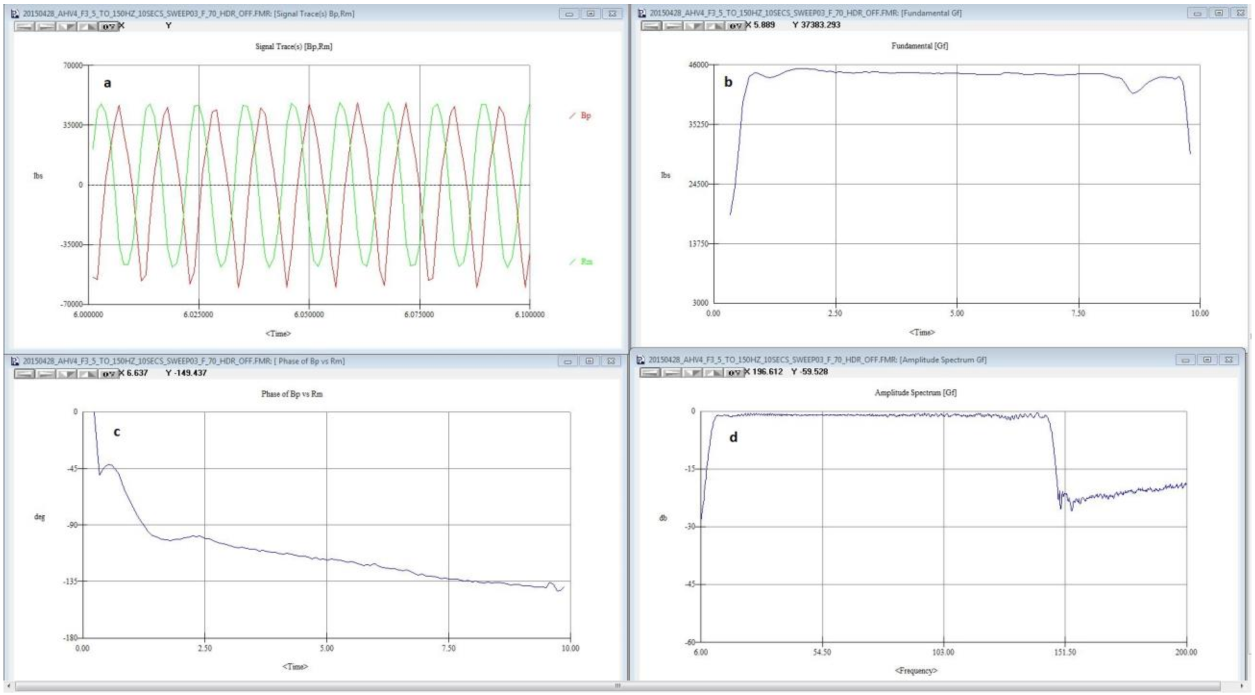

Figure 11 – The AHV-IV 364 vibrator. (a) The wiggle traces of the reaction mass and baseplate accelerations. (b) The fundamental force. (c) The phase difference between the reaction mass acceleration and the baseplate acceleration. (d) The amplitude of the weighted-sum ground force.

If we compare Figure 11c and Figure 7c, we can see that the phase discrepancy of the reaction mass and baseplate accelerations approaching to -135 degrees appears very early in Figure 11 while it appears almost at the end of the sweep in Figure 7. This means that the resonant frequency of the ground in Figure 11 is lower than the resonant frequency of the ground in Figure 7. In other words, the ground in Figure 11 is softer than the ground in Figure 7.

FORCE DRIVE LEVEL FOR SEISMIC VIBRATORS

It is often heard in our industry of a client representative to urge a seismic crew to increase the output drive force to get more energy into the ground. This attitude is often reflected by the statement “I requested these big vibs so that I can generate big signal – now crank that drive level up to 95%”. Unfortunately, the vibrators are not perfect machine. In fact, driving the actuator with a force anywhere near equal to the hold down weight will result in excessive harmonic distortion. This distortion appears as another type of organized noise in our data.

1. Modern vibrator control electronics control the fundamental force output instead of peak force output. For example, a setting of 80% force for a 60,000-lbs vibrator will cause the control electronics attempt to achieve 48,000 lbs of fundamental force. Typically, a distortion level peaking near 27% is common. The S/N (signal-to-noise) ratio of the ground force is 2.96. If the setting is dropped from 80% to 70%, it is normal to see a reduction in harmonic distortion to about 10%. The S/N (signal-to-noise) ratio of the ground force becomes 4.1. Therefore, decreasing 10% of the drivel level can actually improve the S/N ratio of the vibrator ground force.
2. In the previous example, the 27% harmonic distortion level would be equivalent to 16,200 lbs of force. The peak force is the summation of the fundamental force (80%) and

distortion (27%) in the example equivalent to 64,200 lbs. The peak force is very near to the vibrator hold down weight of the vehicle, severe partial decoupling of the baseplate from the earth occurs. Partial decoupling causes cavitation to occur in the servo system of the vibrator. When cavitation occurs, many mechanical parts of the vibrator can be damaged but most often damaged are the servo valve and inline piston accumulators.

Therefore, we must recognize that vibrators are not created only to give us large signals, but rather to create enough potential excess hold down weight to allow the machine to behave in a more controlled, linear manner. Based on extensive testing and research in this area, it has been proven that by setting the drive level to 60% to 75% of available hold down weight will most reliably prevent vibrator decoupling and improve the quality of the force signal driven into the earth.